



# ACT-R 5.0 and Brain Imaging

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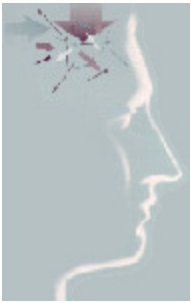
# Outline

- Comments on Cognitive Architectures and ACT-R generally.
- ACT-R 5.0 Architecture
- Study 1. Algebra Equation Solving
- Study 2. Abstract Symbol Manipulation
- Conclusions



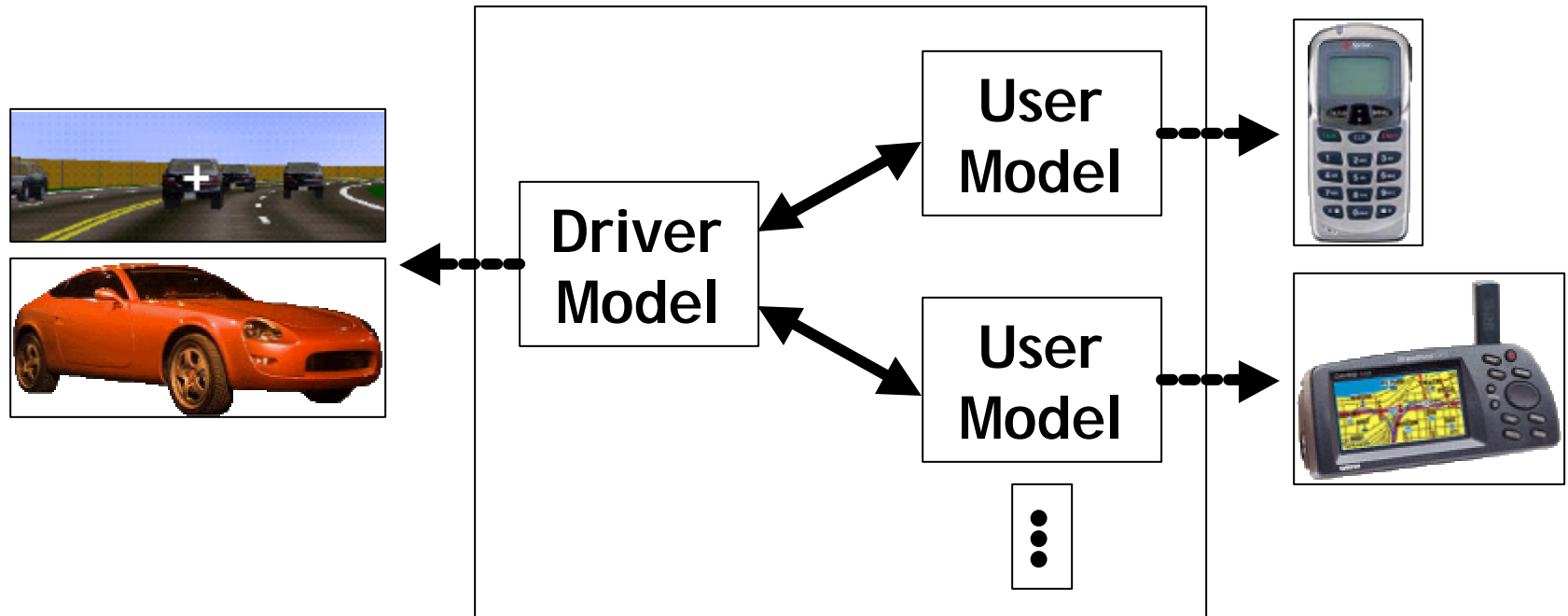
# Motivations for a Cognitive Architecture

1. **Philosophy:** Provide a unified understanding of the mind.
2. **Psychology:** Account for experimental data.
3. **Education:** Provide cognitive models for intelligent tutoring systems and other learning environments.
4. **Human Computer Interaction:** Evaluate artifacts and help in their design.
5. **Computer Generated Forces:** Provide cognitive agents to inhabit training environments and games.
6. **Neuroscience:** Provide a framework for interpreting data from brain imaging.



## An Example: Dario Salvucci's ACT-R Driving Simulation

Cell phone application that integrates cognition, vision, manual, auditory, and speech in a system that actually drives (a simulator) and talks.

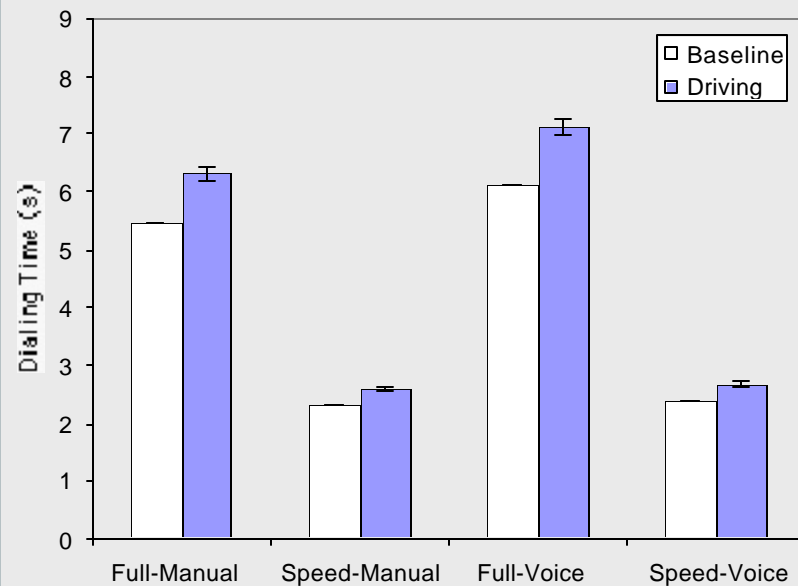




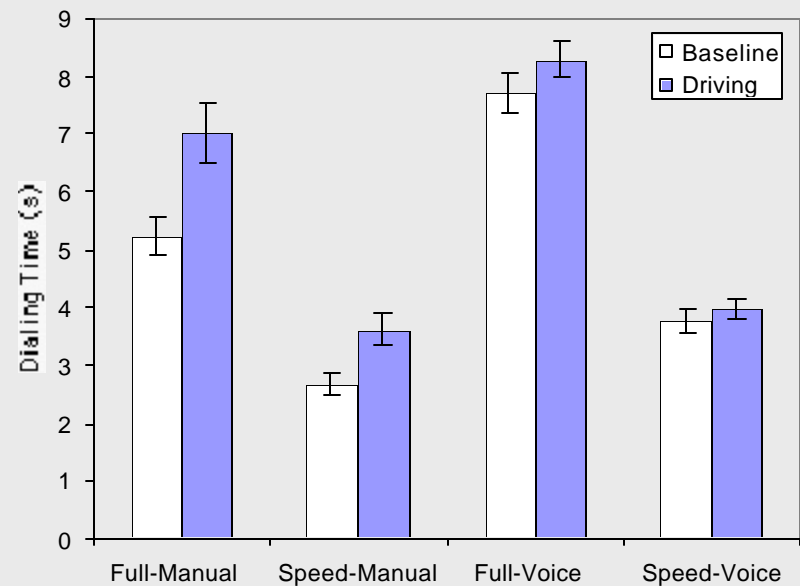
# Study 1: Dialing Times

## ▼ Total time to complete dialing

Model Predictions



Human Data

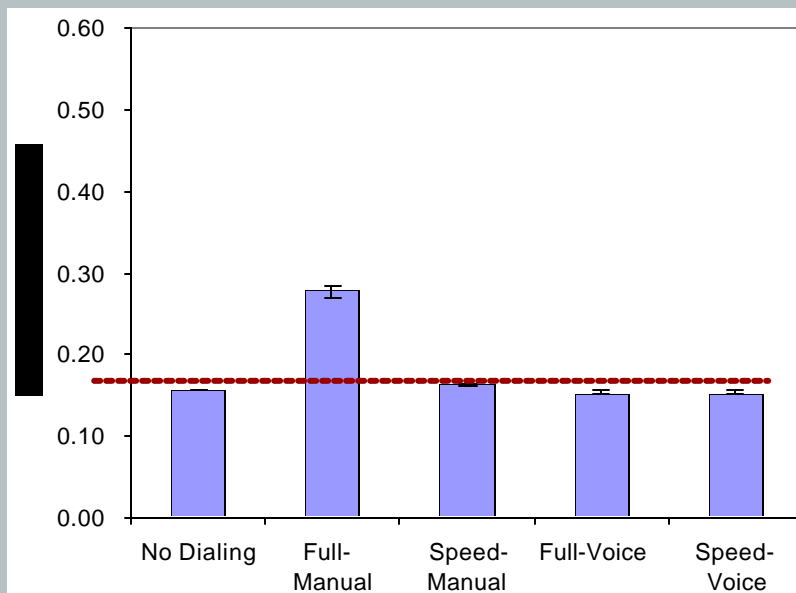




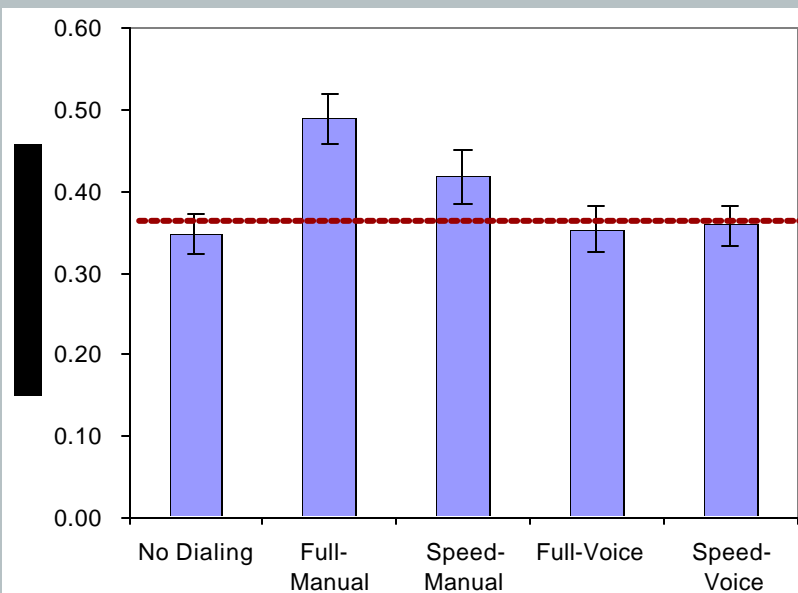
# Study 1: Lateral Deviation

## ▼ Deviation from lane center (RMSE)

Model Predictions



Human Data





## These Goals for Cognitive Architectures Require

1. Integration, not just of different aspects of higher level cognition but of cognition, perception, and action.
2. Systems that run in real time.
3. Robust behavior in the face of error, the unexpected, and the unknown.
4. Parameter-free predictions of behavior.
5. Learning.



# History of the ACT-framework

Predecessor	HAM	(Anderson & Bower 1973)
Theory versions	ACT-E	(Anderson, 1976)
	ACT*	(Anderson, 1983)
	ACT-R	(Anderson, 1993)
	ACT-R 4.0	(Anderson & Lebiere, 1998)
	ACT-R 5.0	(Anderson & Lebiere, 2001)
Implementations	GRAPES	(Sauers & Farrell, 1982)
	PUPS	(Anderson & Thompson, 1989)
	ACT-R 2.0	(Lebiere & Kushmerick, 1993)
	ACT-R 3.0	
	ACT-R 4.0	(Lebiere, 1998)
	ACT-R/PM	(Byrne, 1998)
	ACT-R 5.0	(Lebiere, 2001)
	Windows Environment	(Bothell, 2001)
	Macintosh Environment	(Fincham, 2001)





# Approximately 100 Published Models in ACT-R 4.0 in the Areas of

## I. Perception & Attention

1. Psychophysical Judgements
2. Visual Search
3. Eye Movements
4. Psychological Refractory Period
5. Task Switching
6. Subitizing
7. Stroop
8. Driving Behavior
9. Situational Awareness

## II. Learning & Memory

1. List Memory
2. Fan Effect
3. Implicit Learning
4. Skill Acquisition
5. Cognitive Arithmetic
6. Category Learning
7. Learning by Exploration and Demonstration
8. Updating Memory & Prospective Memory

## III. Problem Solving & Decision Making

1. Tower of Hanoi
2. Choice & Strategy Selection
3. Mathematical Problem Solving
4. Spatial Reasoning
5. Dynamic Systems
6. Use and Design of Artifacts
7. Game Playing
8. Insight and Scientific Discovery

## IV. Language Processing

1. Parsing
2. Analogy & Metaphor
3. Learning
4. Sentence Memory
5. Communication & Negotiation

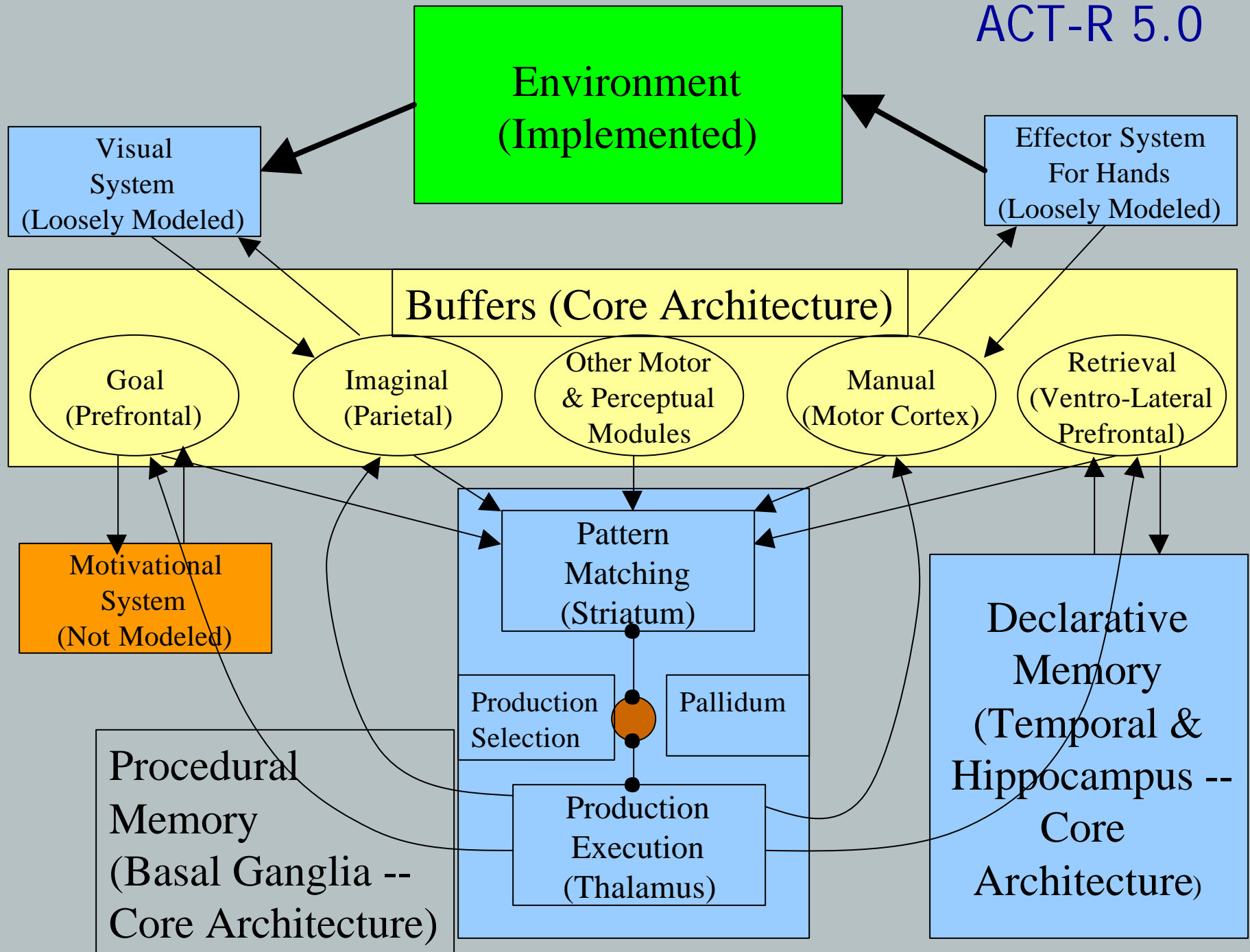
## V. Other

1. Cognitive Development
2. Individual Differences
3. Emotion
4. Cognitive Workload



# The Agenda for Today

- The ultimate goal of the ACT-R theory is to provide a description of human cognition that is at a level that is useful for applications such as training and design.
- While practical application may be the ultimate test of the theory we would like some assurance that the theory provides a veridical approximation to human cognition.
- Traditionally, we have pursued this goal by fitting behavioral data from psychology laboratories.
- However, another measure of “truth” is whether the theory corresponds to brain processes.
- Brain imaging data (in contrast to finer-grain data about single-cell behavior) provides data at a level that is appropriate for judging a high-level architecture like ACT-R.





## ACT-R 5.0 differs from ACT-R 4.0 in

1. Thorough integration with perceptual-motor.
2. Parameter simplification and settling on fixed parameter values.
3. Production learning mechanism.
4. “Buffer” conception of information flow--somewhat akin to Baddeley’s working memory.
5. There is a clear mapping of components onto brain areas.

Note: Everything that worked well in 4.0 continues to work well in 5.0. The code may require transformation to be in the spirit of 5.0, but theoretically this is a matter of cumulative progress.



# Comments on Buffers

- There are currently goal, retrieval, visual, aural, manual, and vocal buffers
- This research is going to want a imaginal buffer (which we are currently implementing as part of the goal buffer). Developing such a buffer seems a high priority task for modeling spatial reasoning and navigation.
- The content that appears in a particular buffer and the timing of its appearance reflects buffer-specific principles but representational assumptions, pattern-matching processes, and production learning should be uniform across buffers.
- The current hypothesis is that these buffers correspond to distinct cortical regions and that the fMRI BOLD response from these regions reflects when these particular buffers are in use. Thus, we can track individual buffer activity with our fMRI data.



# Algebra Experiment

## Extension of Anderson, Reder, & Lebiere (1996)

	No Substitution	Substitution
0 Transformations	$1x+0=06$	$ax+0=c$ ( $a=1$ ; $c=6$ )
1 Transformation	$2x+0=12$ or $1x+9=18$	$ax+0=c$ ( $a=2$ ; $c=12$ )
2 Transformations	$3x+5=23$	$ax+b=23$ ( $a=3$ , $b=5$ )

### fMRI recording

#### Parameters:

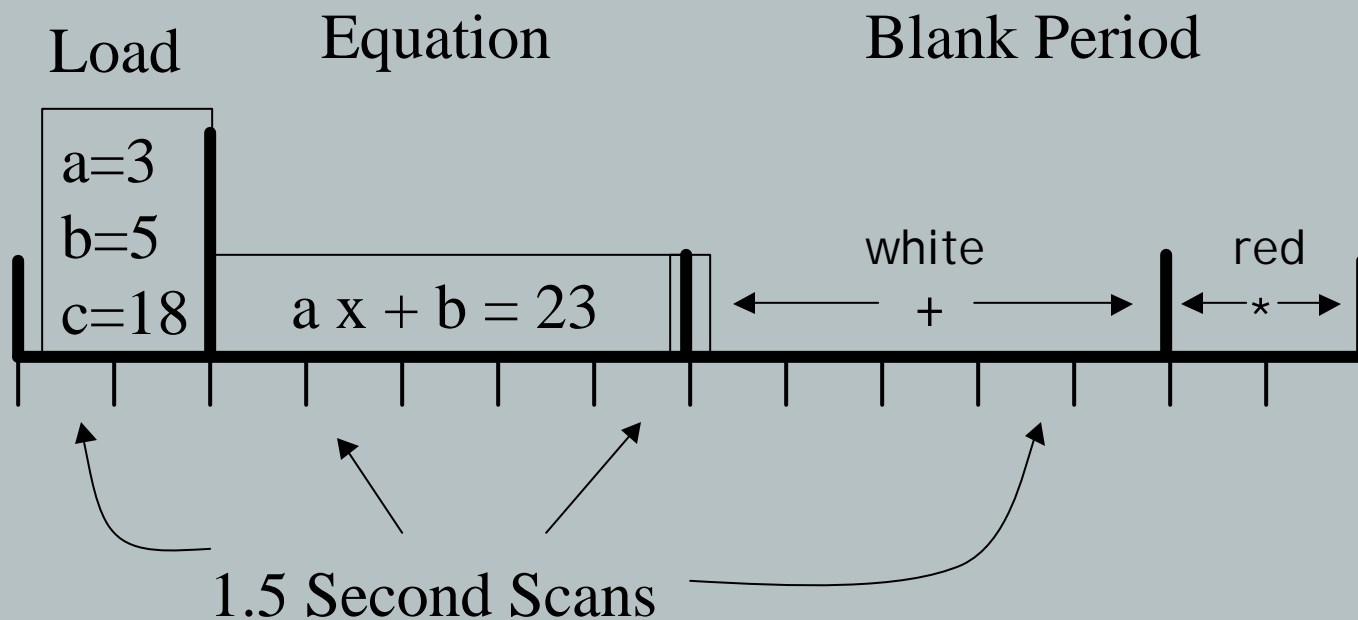
GT 3T, single - shot spiral

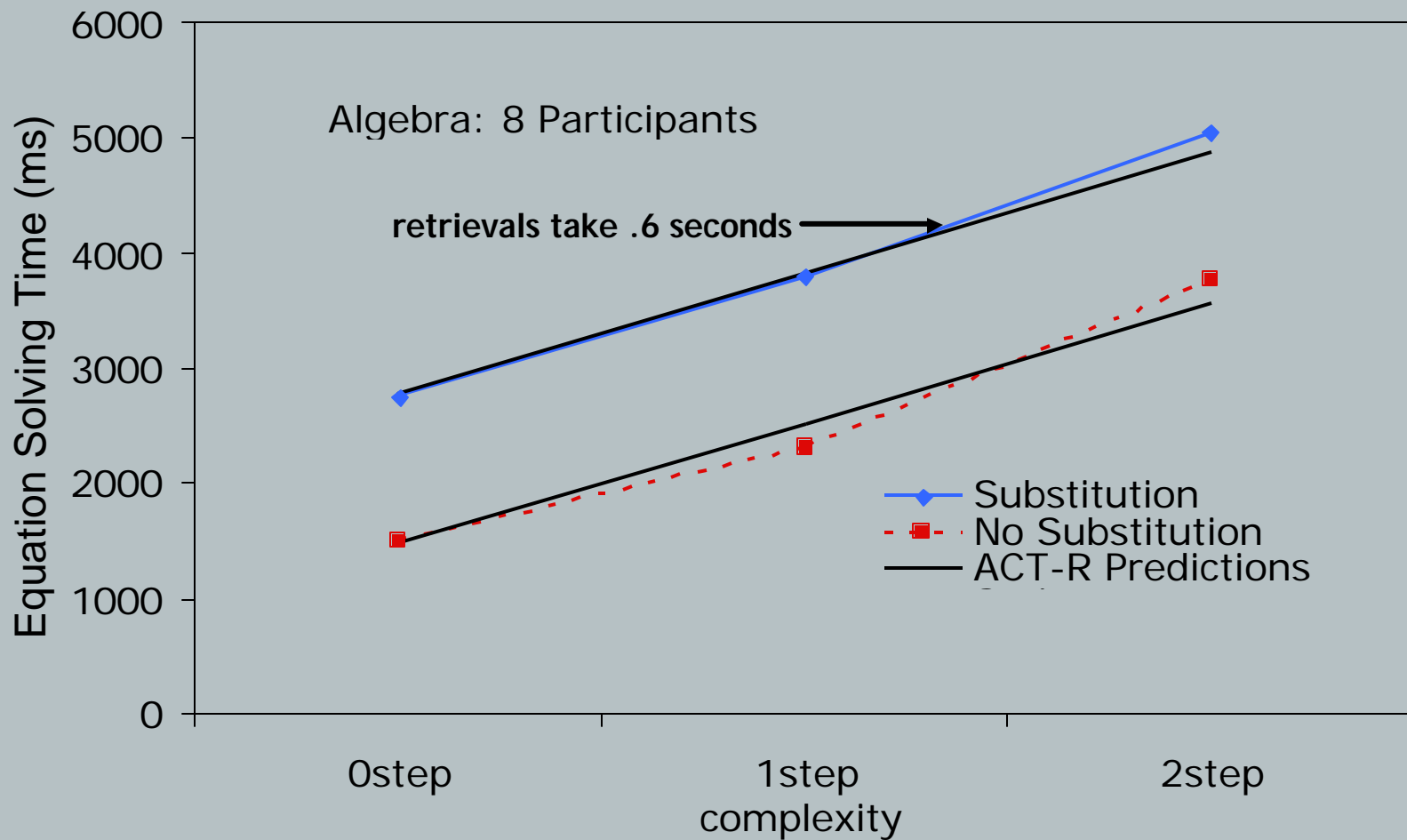
1500 ms TR

28 slices (AC-PC: 8th from the bottom)



## 21 Second Structure of fMRI Trial







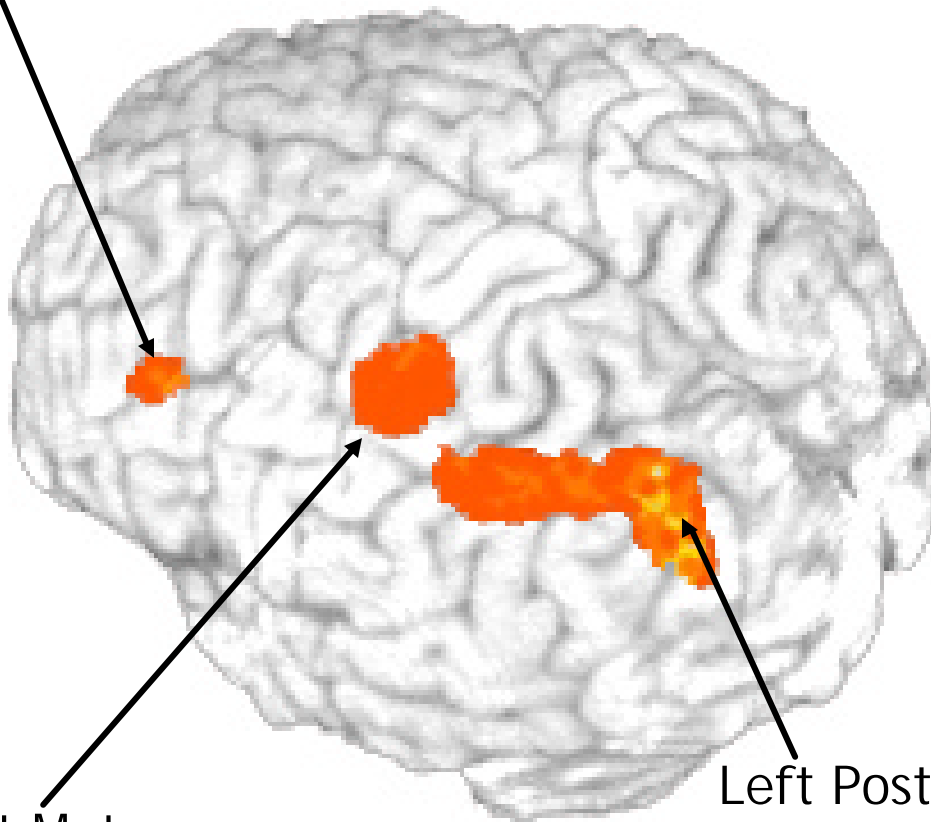


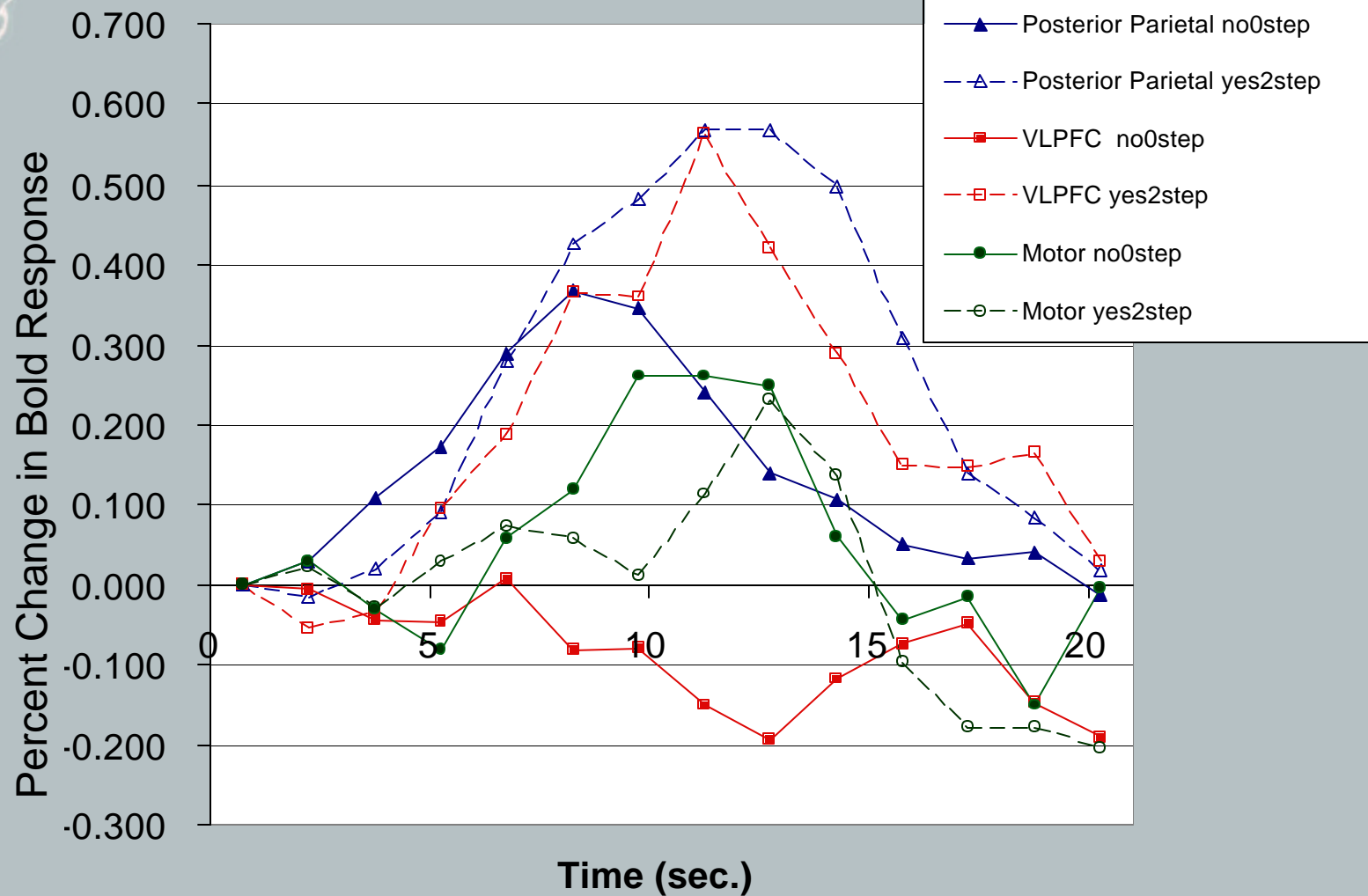
Regions to  
be Modeled  
(Same Regions  
in both studies)

Left Ventrolateral  
Prefrontal Cortex  
(BA 45/46)

Left Motor  
(BA 1-4)

Left Posterior  
Parietal  
(BA 39/40)







ACT-R  
Buffer  
Activity  
during  
Solution of  
 $ax + 3 = c$

Time	Imaginal	Retrieval	Manual
3.1	$\_ = c$		
3.3			
3.5		$c = 24$	
3.7			
3.9	$\_ = 24$		
4.1	$\_ 3 = 24$		
4.3	$+ 3 = 24$		
4.5		$-$ is inverse of $+$	
4.7			
4.9			
5.1			
5.3		$24 - 3 = 21$	
5.5			
5.7	$\_ = 21$		
5.9	$a X = 21$		
6.1		$a = 3$	
6.3			
6.5			
6.7	$3 X = 21$		
6.9		$21/3 = 7$	
7.1			
7.3	$X = 7$		
7.5			key 7
7.7			



## Associations of Regions with Buffers

1. The posterior parietal region corresponds to the visual imaginal buffer (e.g., Reichle, Carpenter, & Just 2000).
2. The VLPFC region corresponds to the retrieval buffer (e.g., HERA model).
3. The motor region corresponds to the manual buffer (an uncontroversial anchor).



Basic proposal (Boyton, 1996; Dale & Buckner, 1997; Cohen, 1997) for the shape of fMRI response to an event  $t$  times units ago is:

$$B(t) = t^a e^{-t}$$

Observed fMRI response is integrated over time the buffer is active. Therefore

$$CB(t) = M \int_0^t i(x) B\left(\frac{t-x}{s}\right) dx$$

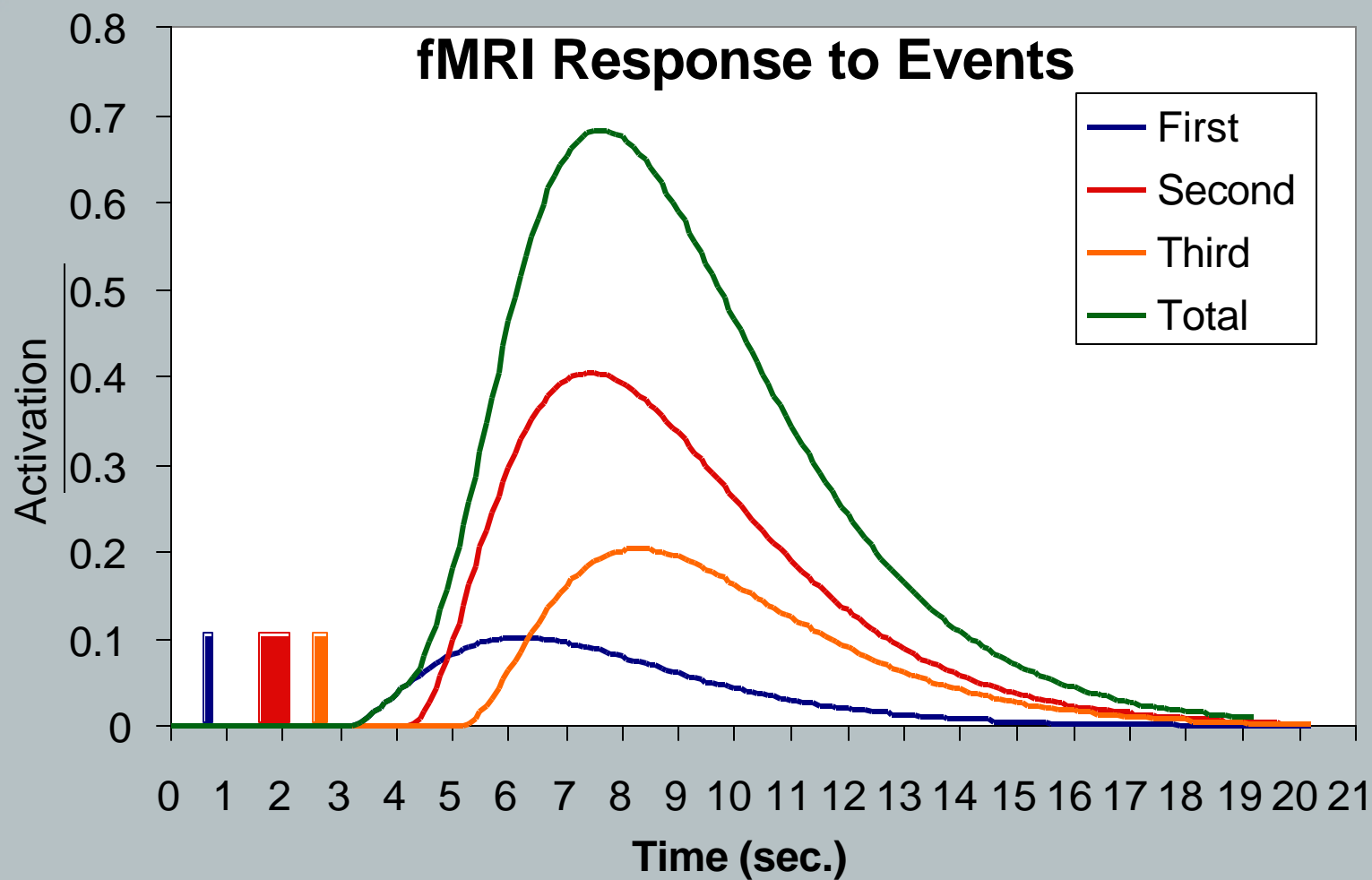
where

$M$  = magnitude scale for response (estimated values 3.24 for imaginal, 1.10 retrieval, and 4.88 motor)

$s$  = latency scale (estimated value 1.38 sec.)

$i(x)$  = 1 if buffer occupied at time  $x$ , 0 otherwise

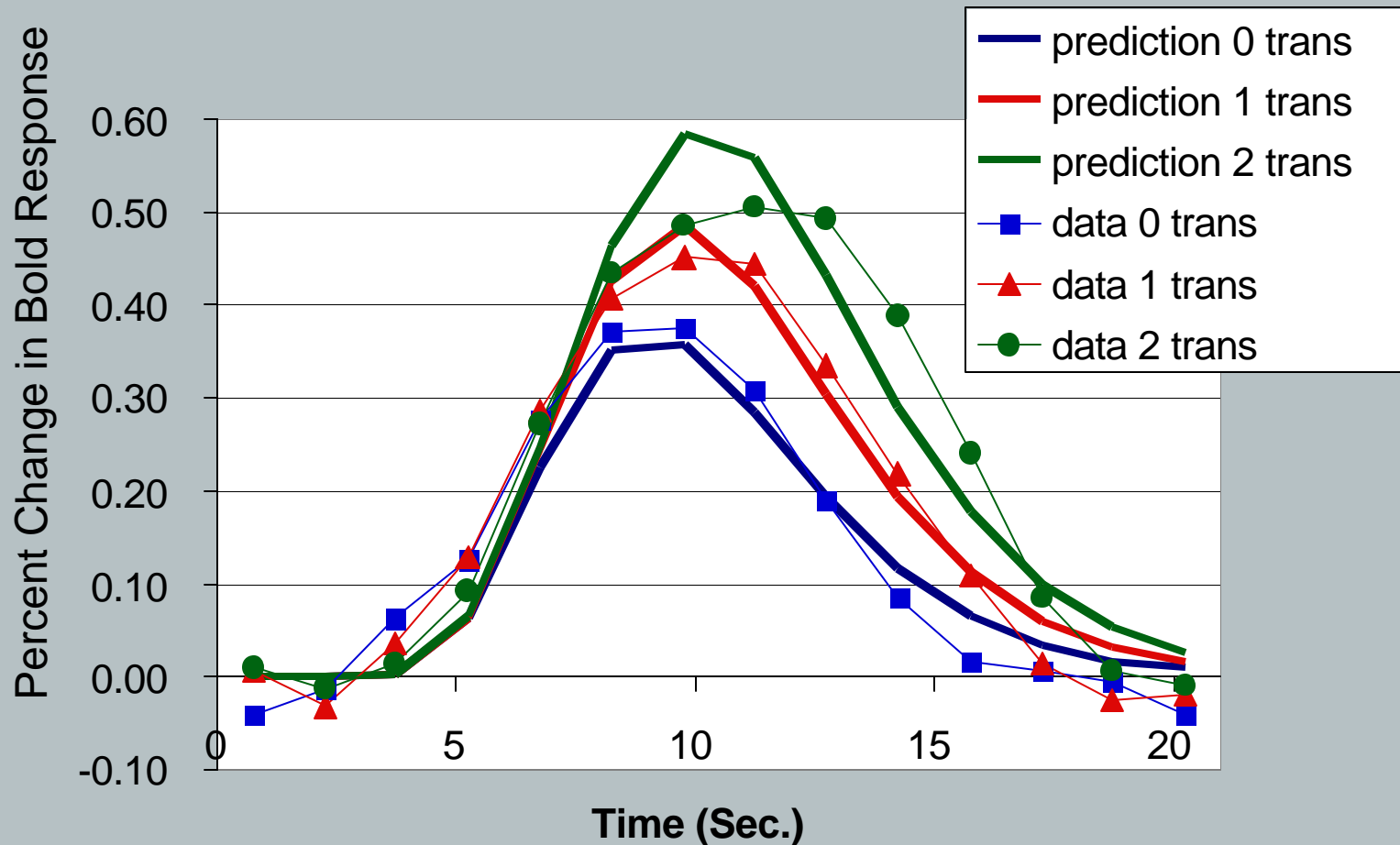
$a$  = exponent (estimated value 3.67)





## Imaginal Predicts Posterior Parietal

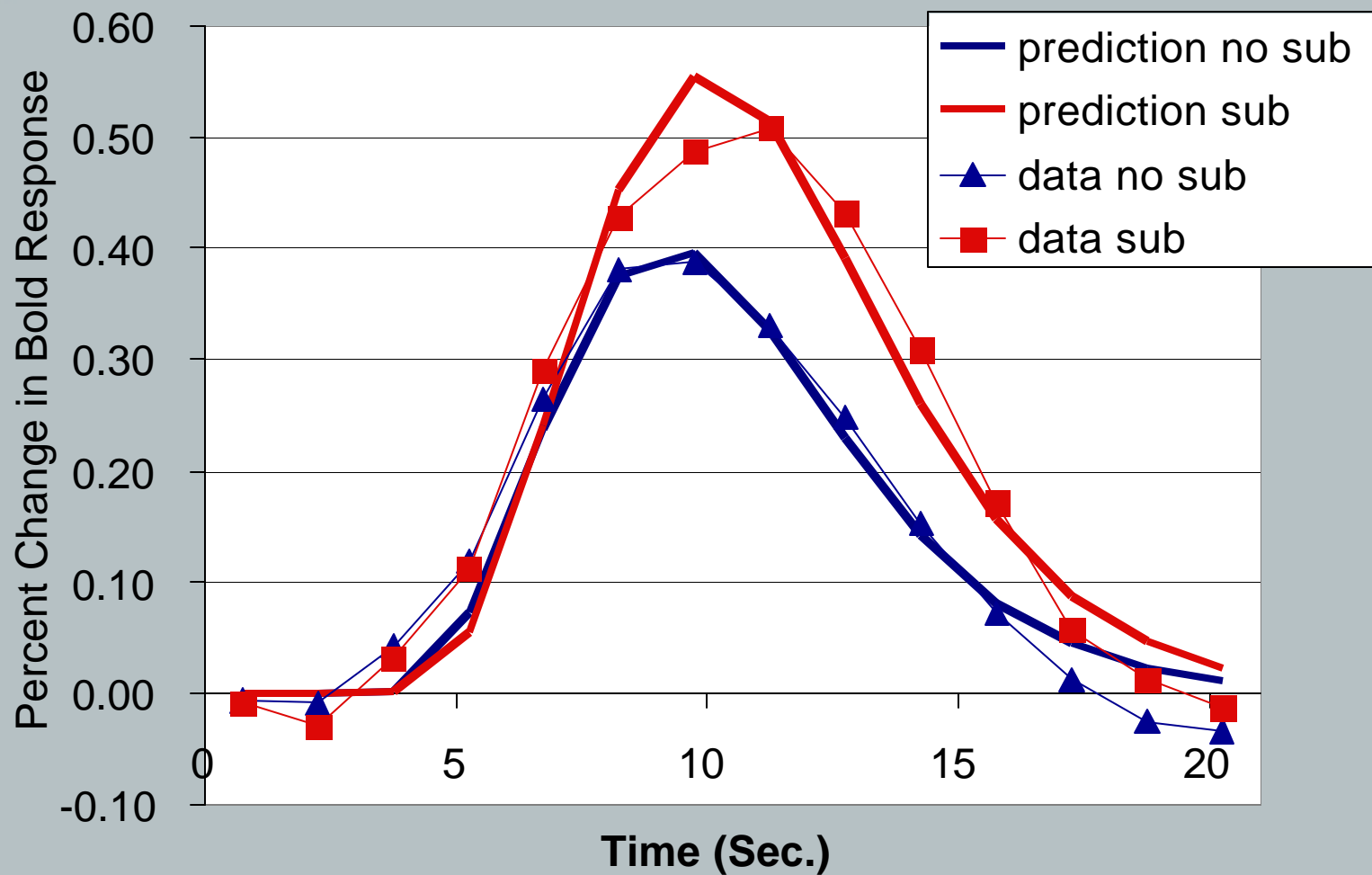
$r = .998$





## Imaginal Predicts Posterior Parietal

$r = .998$

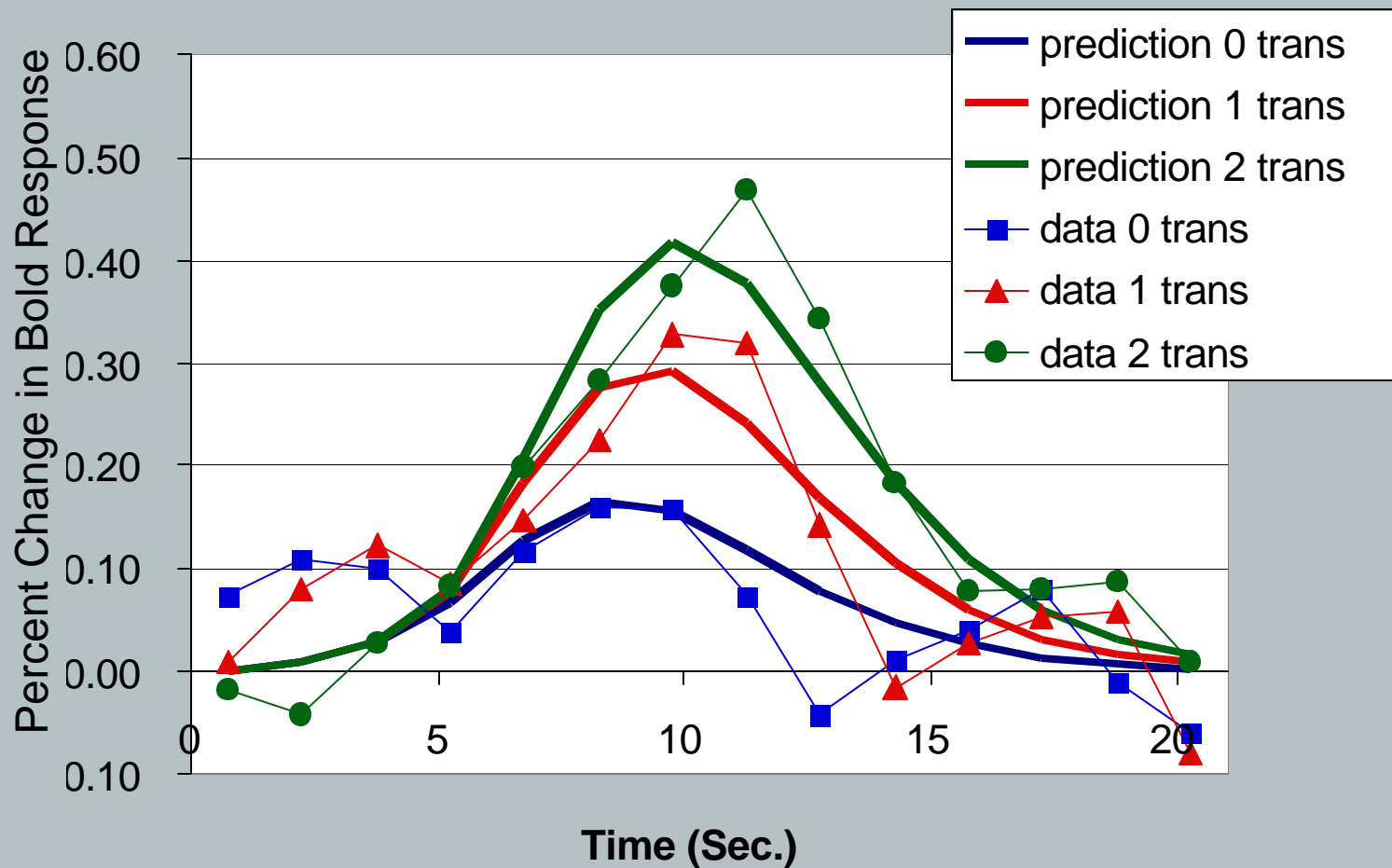






## Retrieval Predicts VLPFC

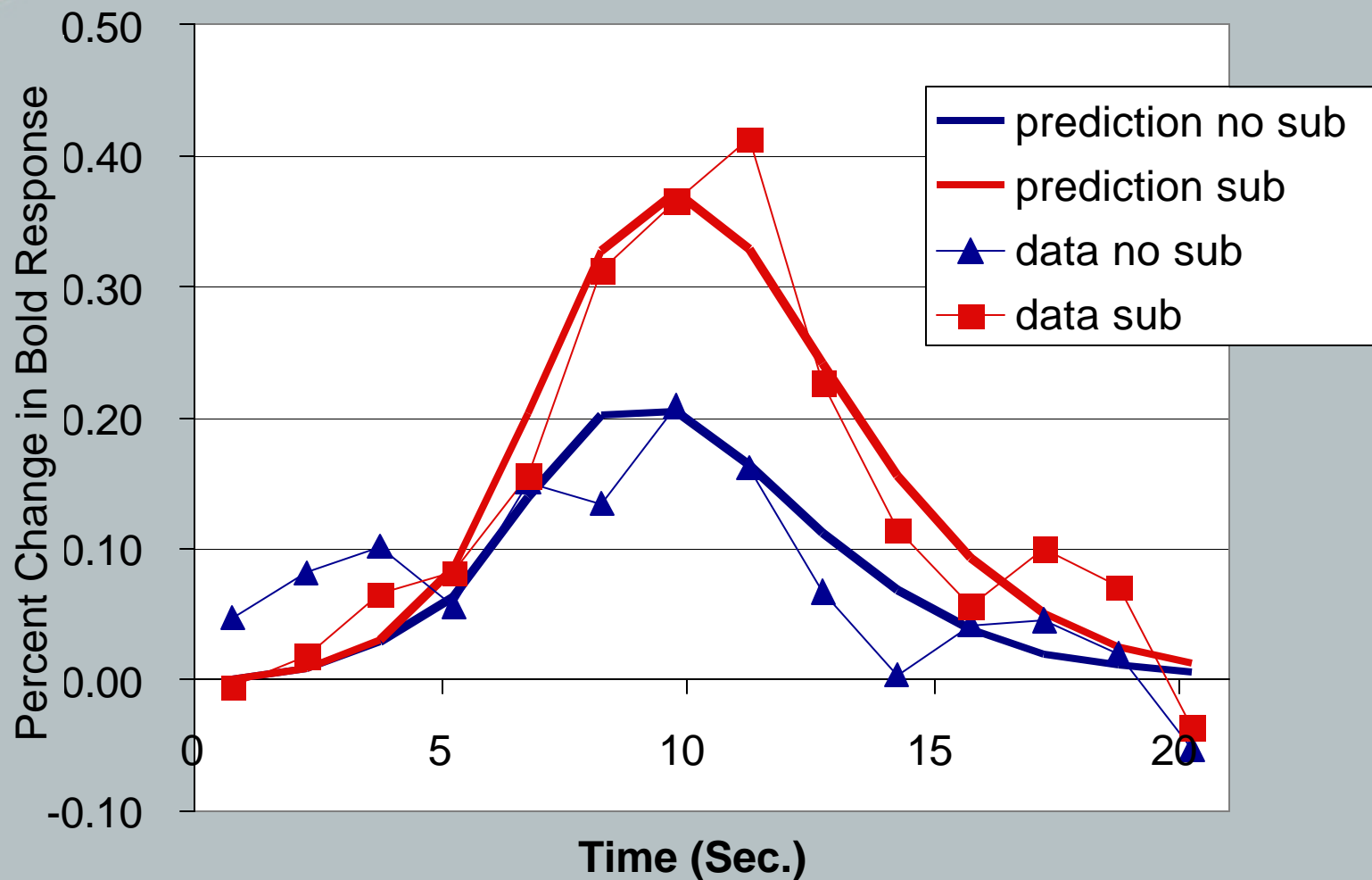
$r = .991$





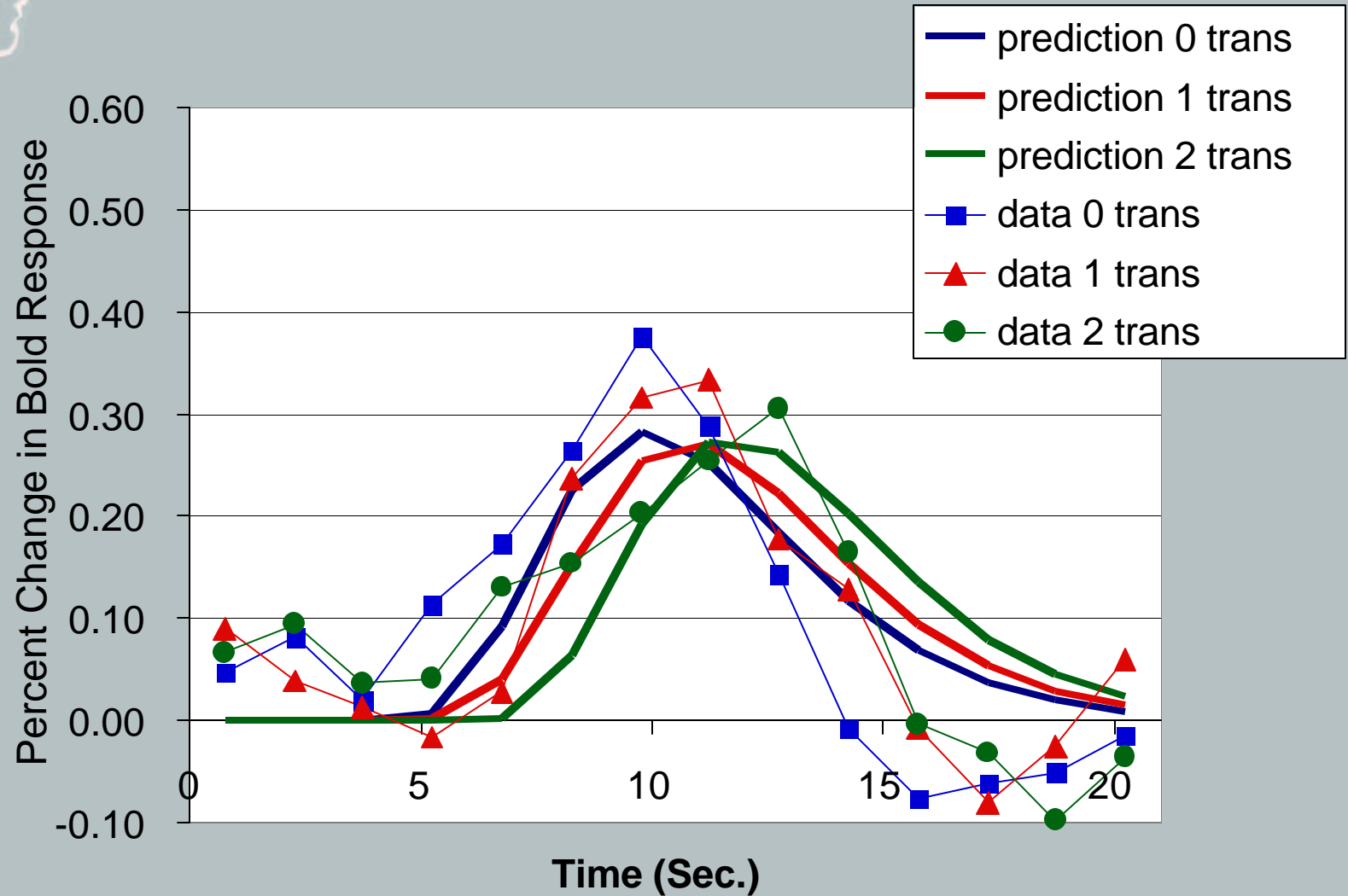
## Retrieval Predicts VLPFC

$r = .994$



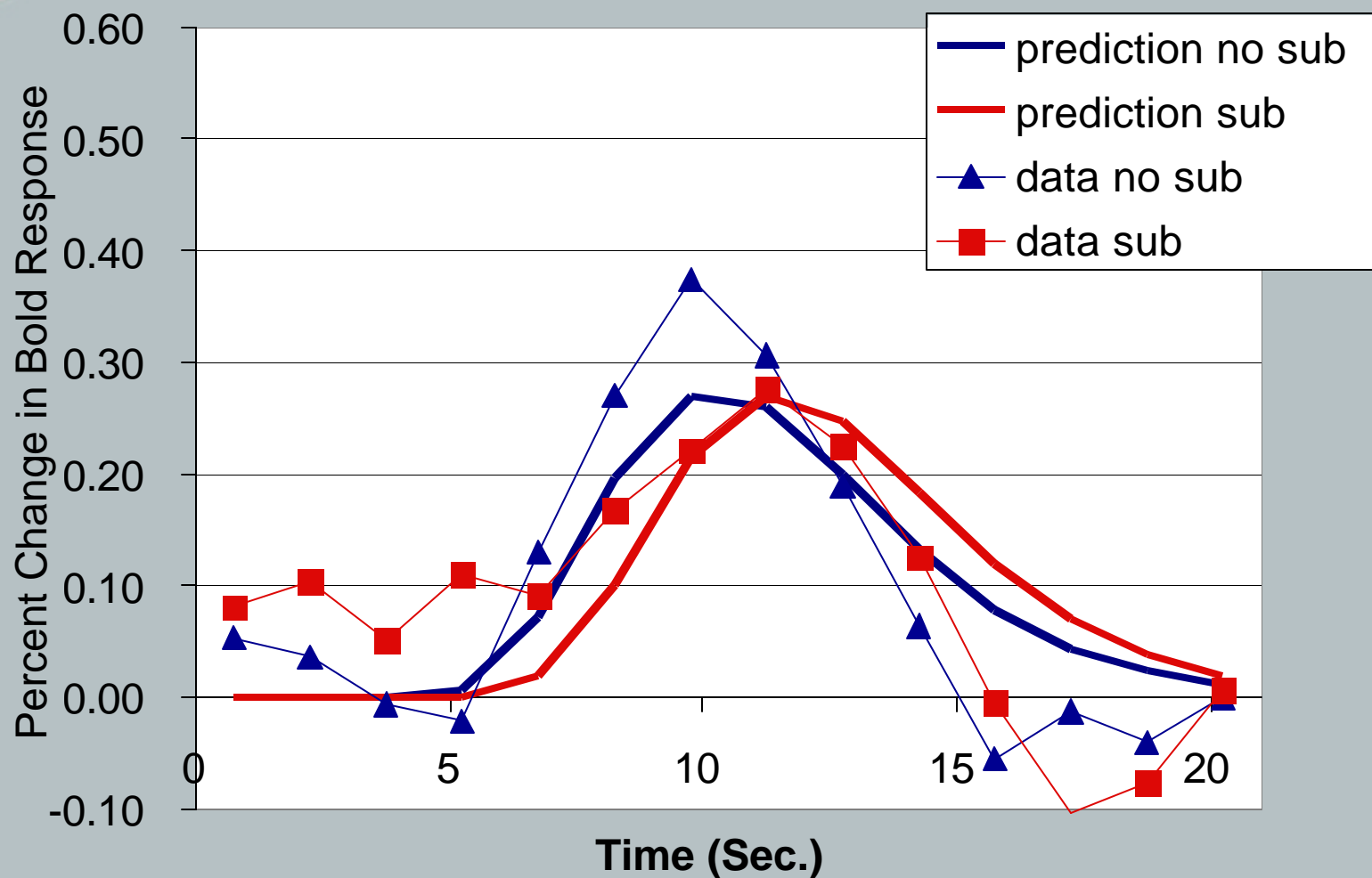


## Manual Predicts Motor, $r = .972$





## Manual Predicts Motor, $r = .973$





## Symbolic Reasoning Experiment Based on Blessing & Anderson (1996)

Example of equations:

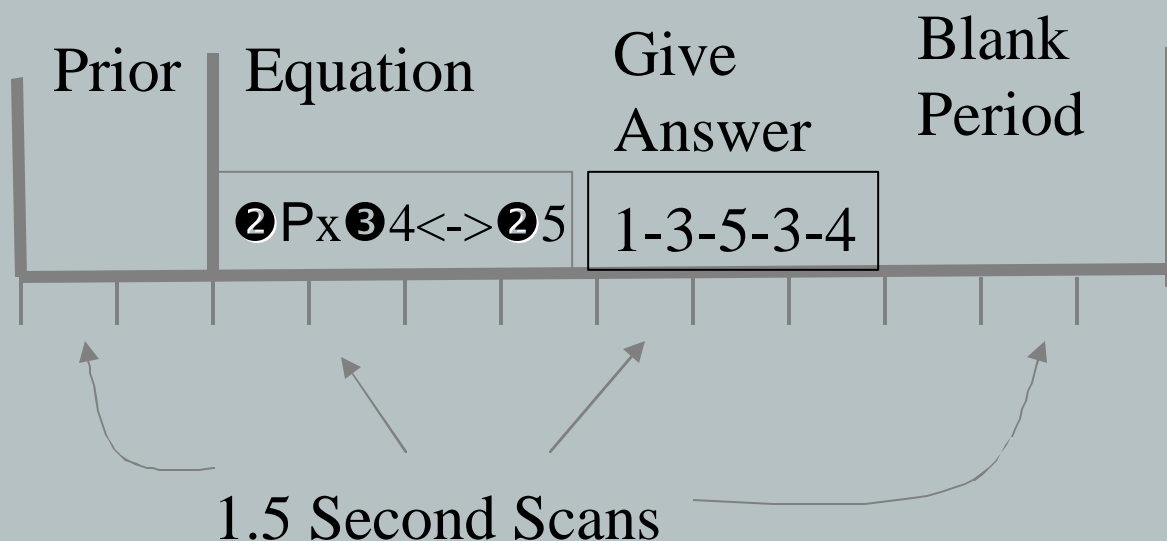
step	equation	answer
0 step	$P \leftrightarrow \textcircled{3}4 \textcircled{2}5$	$P \leftrightarrow \textcircled{3}4 \textcircled{2}5$
1 step	$\textcircled{2}P \leftrightarrow \textcircled{3}4 \textcircled{2}5$	$P \leftrightarrow \textcircled{2}4 \textcircled{3}5$
2 step	$\textcircled{2}P \textcircled{3}4 \leftrightarrow \textcircled{2}5$	$P \leftrightarrow \textcircled{3}5 \textcircled{3}4$

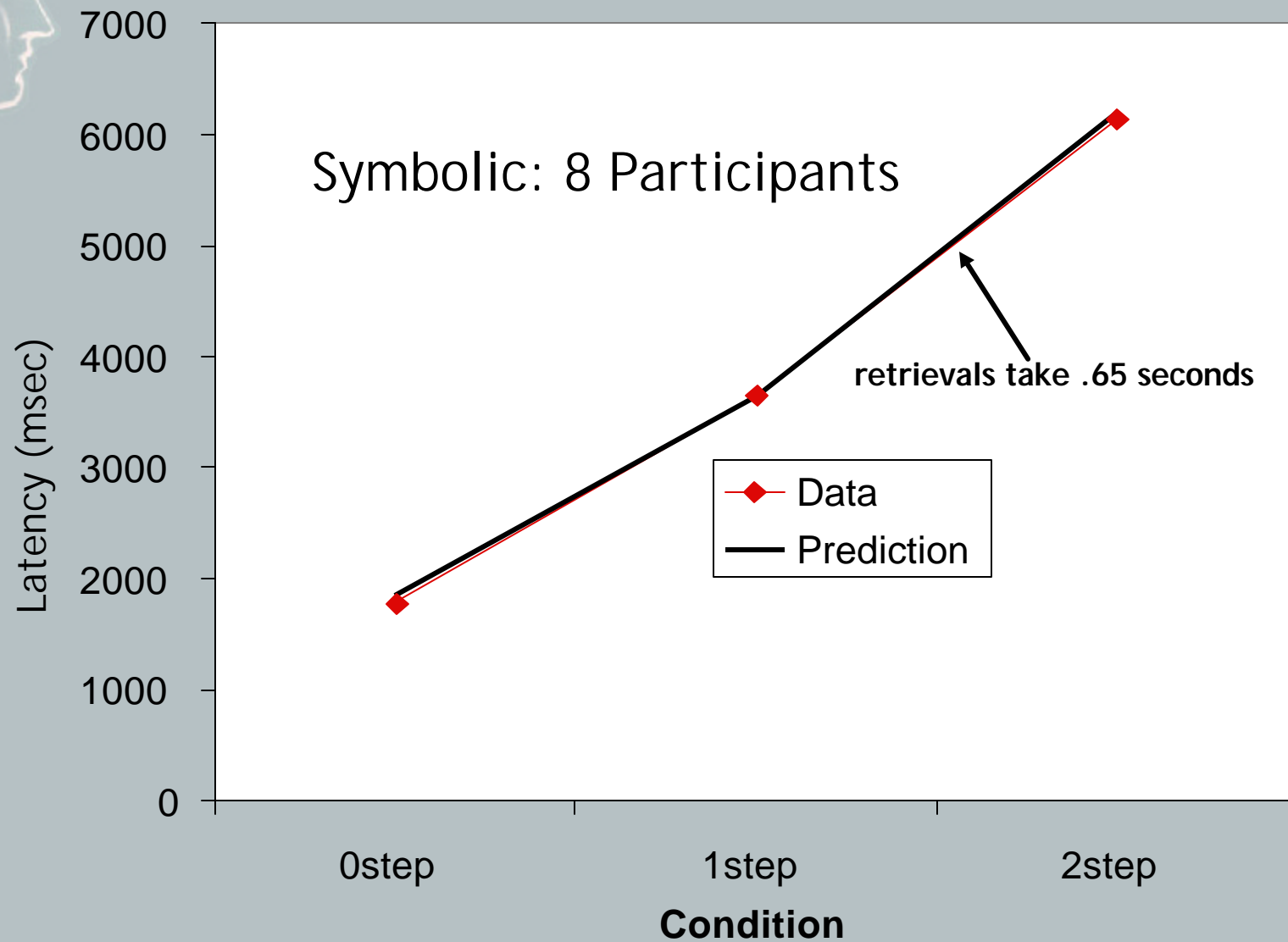
Subject types answer by pressing thumb and then keying 4 terms at the rate of one per 1.5 seconds.

Same fMRI scanning procedure.



## 18 Second Structure of fMRI Trial



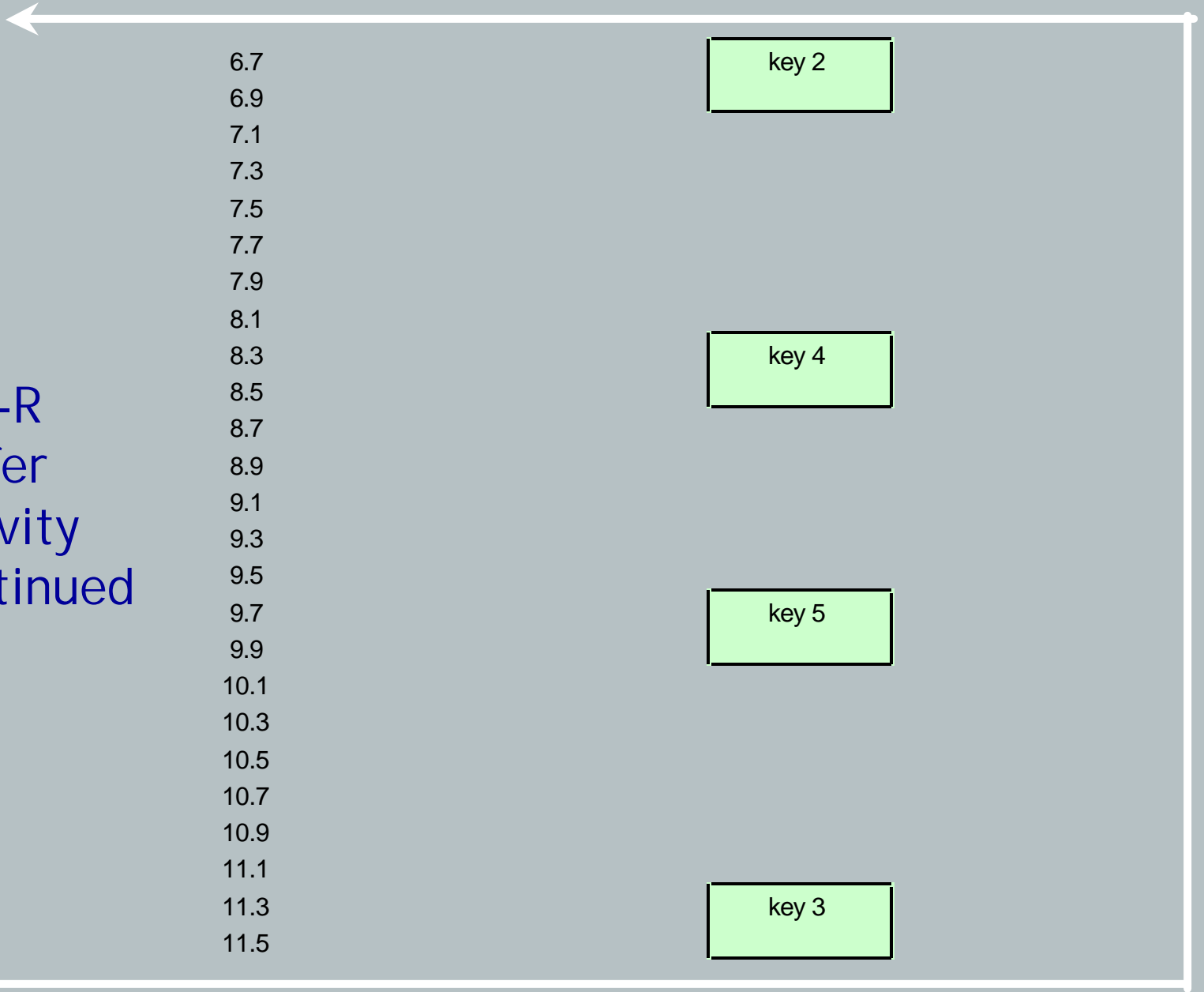




ACT-R  
Buffer  
Activity  
during  
Solution of  
 $3\text{ P} \leq 2354$

Time	Imaginal	Retrieval	Manual
3.1			
3.3	$\leq 2$		
3.5	$\_ \leq 23$		
3.7	$\leq 235$		
3.9	$\_ \leq 2354$		
4.1			
4.3	$\text{P} \leq 2354$		
4.5	$3\text{P} \leq 2354$		
4.7		$3$ means flip  args in 2nd and 4th positions	
4.9			
5.1			
5.3			
5.5			
5.7			
5.9	$\text{P} \leq 245 \_$		
6.1	$\text{P} \leq 2453$		
6.3			key 1
6.5			
6.7			key 2
6.9			







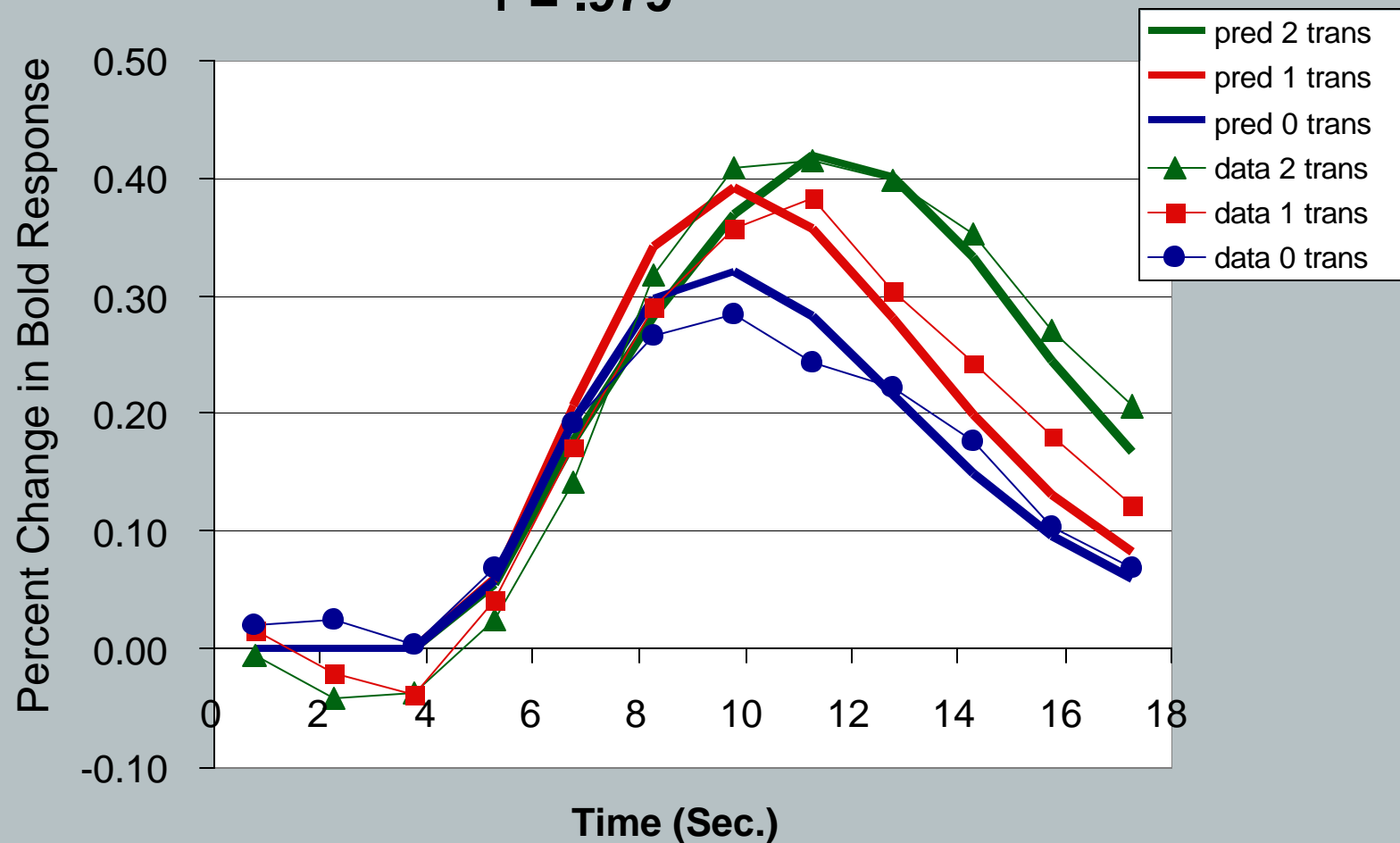
## Comparison of Fits

	Algebra	Symbolic
Scale (s)	1.384	1.761
Exponent (a)	3.670	2.920
M Imaginal	3.241	2.033
M Retrieval	1.097	0.923
M Motor	4.878	4.068
$R^2$ Imaginal	0.964	0.979
$R^2$ Retrieval	0.899	0.928
$R^2$ Motor	0.608	0.978



## Imaginal Predicts Posterior Parietal

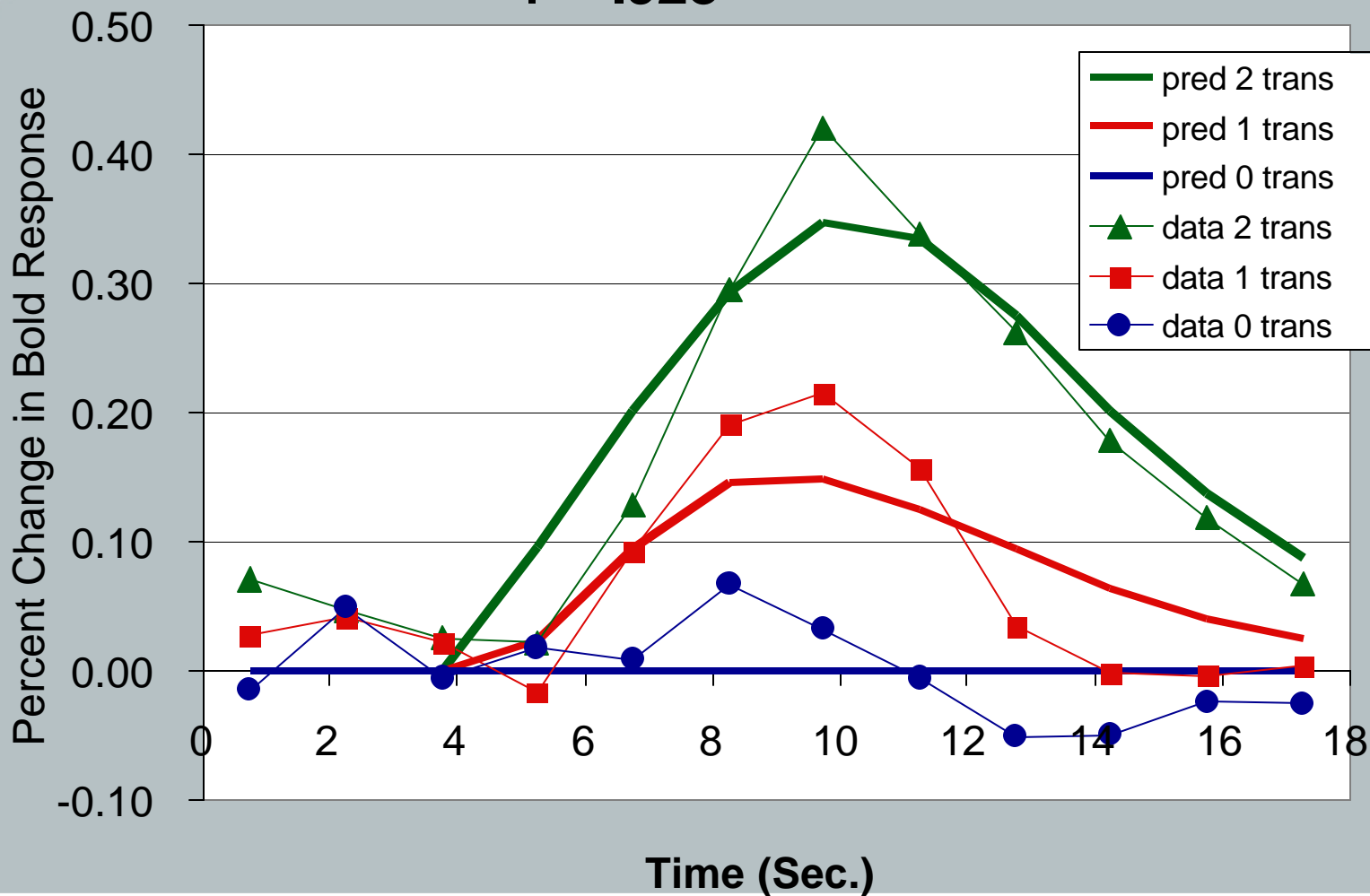
$r = .979$



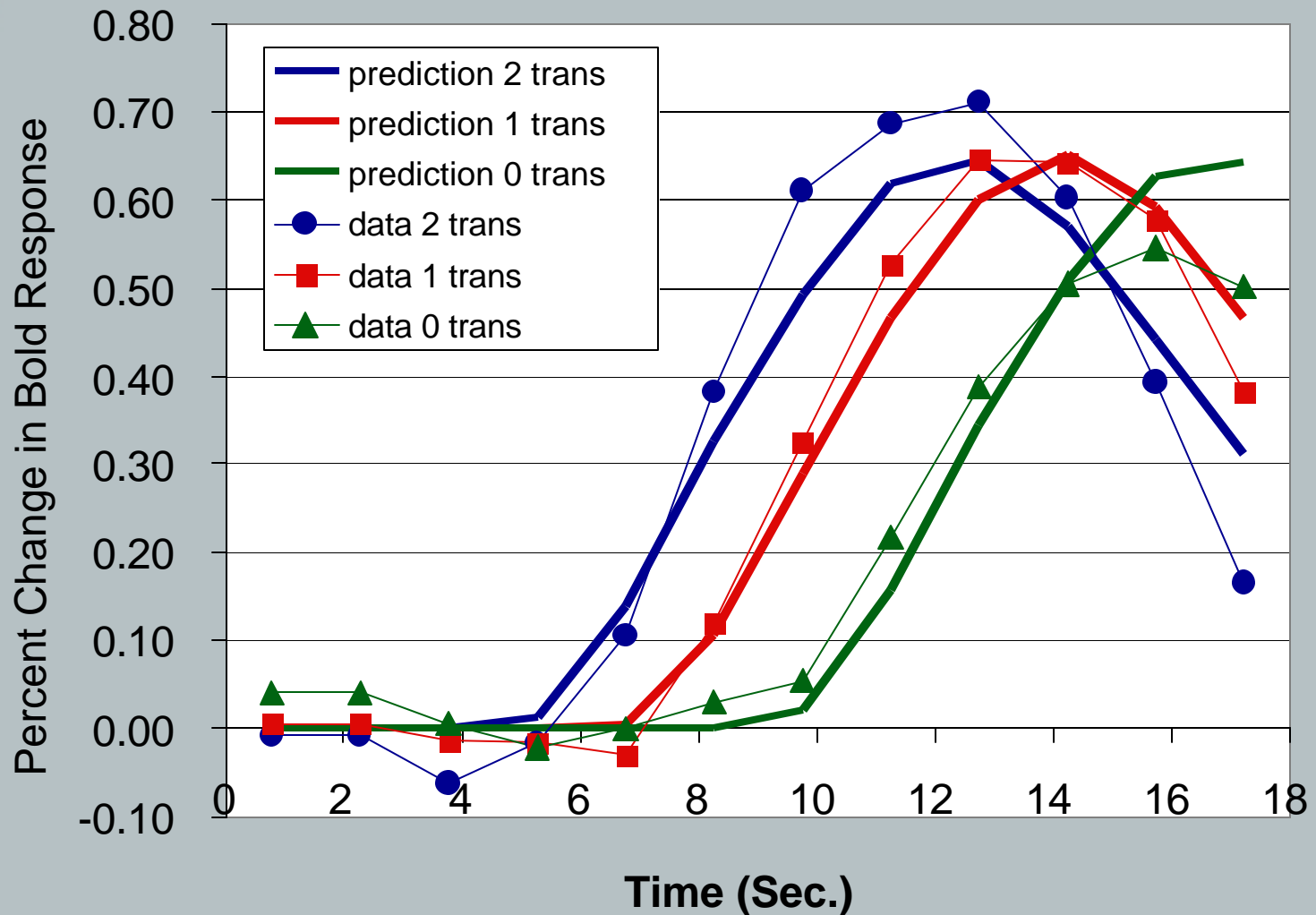


## Retrieval Predicts VLPFC (BA 46)

$r = .928$



## Manual Predicts Motor, $r = .978$





## Modules and Complex Cognition: Conclusions

1. The time course of relatively complex tasks like mental algebra is well suited to an event-related fMRI study
2. A cognitive model like ACT-R can predict the BOLD function by tracking the time when various modules are operative. This can be deconfounded from total time.
3. The posterior parietal cortex seems to be part of the module responsible for transformations in problem representation (actually bilateral in the symbolic study).
4. The left ventro-lateral prefrontal cortex seems to be part of the module responsible for retrieval of critical information from declarative memory.
5. Data on the behavior of such modules promise to constrain what have been relatively unconstrained models of complex processes.